| *Notice of References Cit d* | Application/Control No. 09/872,895 | Applicant(s)/Patent Under Reexamination ARSHAD ET AL. | |
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| | Examiner Kevin Pyo | Art Unit 2878 | Page 1 of 1 |

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*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

S/N 09/750,866 filed 12/28/00

# LASER BASED REFLECTIVE BEAM CYLINDER SENSOR

## FIELD OF THE INVENTION

The invention relates to measuring the excursion of hydraulic actuators using laser time-of-flight techniques. More particularly, it relates to linear hydraulic cylinders having laser light pulse emitters and laser light detectors reflecting off moving internal surfaces of the hydraulic cylinder.

## BACKGROUND OF THE INVENTION

With the increased computerization of traditionally mechanical and hydro-mechanical systems, the ability to accurately control and position a wide variety of agricultural and construction equipment has become possible. Using proportional control valves and hydraulic server motors, agricultural and construction vehicles have been designed that can compensate for a wide variety of environmental variables to much more accurately control the motion and positioning of their various arms and linkages.

To provide the ever-more-accurate positioning and control that microprocessors are capable of, one must know ever more accurately the exact position of the various linkages, arms and actuators that comprise these vehicles. Other methods of determining the location of mechanical components of these vehicles included such things as rotary potentiometers and resistors mounted at pivoting joints, linear variable differential transformers coupled to the outside of

extendable devices such as hydraulic cylinders that extend and retract, and linear variable resistors.

These older methods of determining the location of various components of the vehicles are now seriously outmoded. In particular, many of these components include several moving parts that are exposed to the elements, and therefore are prone to be broken, bent or otherwise become un-calibrated.

What it need, therefore, is a more robust system of determining the position of vehicle components that reduces the risk of breakage, mis-calibration, and provides a greater positional accuracy than these previous devices. It is an objective of the present invention to provide such a system.

## SUMMARY OF THE INVENTION

In accordance with a first embodiment of the invention, a fluid actuated cylindrical actuator is provided that includes a cylinder having first and second ends, an end cap fixed to the first end of the cylinder and having a rod opening, a piston disposed in the cylinder, a rod coupled to the piston and extending from inside the cylinder to outside the cylinder and passing through the rod opening, a first light guide extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder and to bar the passage of the fluid, and second light guide extending from inside the cylinder to outside the cylinder and adapted to transmit the at least a first beam of laser light at the first frequency from inside the cylinder to outside the cylinder and to bar the passage of fluid. The first light guide may be disposed to transmit the first beam of laser light substantially along a longitudinal axis of the cylinder such that the first beam impinges on a reflective portion of the piston over substantially an entire range of piston travel. The second light guide may be disposed to receive the first beam after it has been reflected off the piston. The optical distance between the first light guide and the second light guide may be a function of the degree of extension of the rod outside the cylinder. The first

beam of light may be reflected off a first surface inside the cylinder where the first surface is coupled to the rod and configured to move with the rod. The first beam of light may be reflected off a second surface fixed with respect to the cylinder and movable with respect to the rod and a third surface fixed with respect to the rod and movable with respect to the cylinder. The first beam may vary in optical length when the rod is moved with respect to the cylinder an amount equal to at least four times an axial distance the rod travels.

In accordance with a second embodiment of the invention, a hydraulic actuator for an agricultural or construction vehicle is provided, the actuator including a cylinder having a substantially circular internal diameter and a longitudinal cylindrical axis, a piston having a substantially circular outer diameter and configured to be received in and hydraulically sealed against the inner diameter of the cylinder, a piston rod with a substantially circular outer rod diameter that is fixed to the piston and extends from the piston inside the cylinder, through a first end wall of the cylinder to a location outside the cylinder, wherein the first end wall is disposed to enclose and seal a first end of the cylinder and is substantially perpendicular to the longitudinal axis of the cylinder, a second end wall fixed to the cylinder and disposed to seal a second end of the cylinder substantially perpendicular to the longitudinal axis of the cylinder, the second end wall including a first optical path configured to transmit a beam of laser light through the second end wall to a reflective surface fixed to the piston and further including a second optical path configured to transmit the reflective beam of laser light back through the end wall, a first optical fiber optically and mechanically coupled to the second end wall to transmit the beam of laser light from a remote laser light source to the first optical path and a second optical fiber optically and mechanically coupled to the second end wall to transmit the reflected beam of laser light to a remote laser light receiver.

The first and second optical paths may include at least one hermetically sealed fiber optical feed-through or connector extending through the second end wall. At least one fiber optic feed-through or connector includes an adjustable focal length lens disposed in the beam of laser light and configured to adjust a focal length of the beam of laser light within the cylinder. At least one fiber optic feed-through or connector

may include a threaded end cap with the adjustable focal length lens fixed to the end cap. The hydraulic actuator may include another hermetically sealed fiber optic feed-through or connector extending through the second end wall. The first and second optical fibers may be multi-modal optical fibers. The actuator may also include a first laser diode configured to emit a beam of laser light at a wavelength in the range of 840 to 980 nanometers. The hydraulic actuator may also include a first photo-diode configured to receive the beam of reflective laser light and generate an electrical signal indicative of at least one characteristic of the beam. The actuator may also include a second laser diode configured to emit the beam of laser light in the range of 430 to 1300 nanometers. The actuator may include a second photo diode configured to receive a beam of laser light and generate an electrical signal indicative of at least one characteristic of the beam.

In accordance with a third embodiment of the invention, a method of determining the position of the piston of the actuator described in the previous paragraph includes the steps of generating the beam of laser light, reflecting the beam of laser light off a surface fixed to move axially with the piston, receiving the reflected beam of laser light, and calculating a time-of-flight. The step of generating the beam may include the step of generating the beam with a wavelength of between 430 and 1300 nanometers. The step of generating the beam may include the step of generating the beam with a wavelength in the range of 840 and 980 nanometers. The step of generating the beam may include the step of generating a sequence of individual pulses of light, and the step of calculating a time-of-flight may include the step of determining the time-of-flight of at least one pulse in the sequence of individual pulses of light.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a partial cross-sectional view of a hydraulic actuator having the laser-based reflective beam sensor and a control unit for generating the laser beam and calculating the position of the actuator wherein the laser light sources are located

remotely from the actuator and cables including two fiber optic light guides couple the control unit to the actuator;

FIGURE 2 illustrates an alternative embodiment of a hydraulic actuator of FIGURE 1 in which the laser light sources are located at the actuator and cables including two electrical conductors couple the control unit to the actuator; and

FIGURE 3 is a detailed view of the embodiment of FIGURE 2 showing the feed-throughs or connectors 46 and 48 in more detail, as well as the fiber optic cables and the connections at control unit 39.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIGURE 1 is a schematic view of a linear cylindrical actuator 10 in accordance with the present invention. Actuator 10 includes a cylinder 12 having an inner diameter 14 and two end caps 16, 18. Rod end cap 16 encloses one longitudinal end of the cylinder and has an opening 17 through which rod 24 passes. Opening 17 seals against the surface of the rod and prevents actuating fluid from leaking out. End cap 18 encloses the opposing end of the cylindrical potion of the cylinder and prevents actuating fluid from leaking out.

Actuator 10 also includes a piston assembly 20 which includes a piston 22 having an outside diameter 23 configured to seal against the inner diameter 14 of the cylinder and to slide longitudinally, back and forth, with respect to cylinder 12. Piston 22 is coupled to rod 24, which extends from the inside of the cylinder to the outside of the cylinder through opening 17 and is fixed to piston 22 to move simultaneously with the piston. A reflective surface 26 is fixed to piston 22 and is configured to reflect laser light that is introduced into the cylinder. Two ports 28, 30 are provided in the cylinder to introduce an operating fluid into the cylinder or remove the operating fluid from the cylinder. Extension cylinder port 28 is disposed in the cylinder such that fluid introduced into the port will cause the piston and piston rod to move in a direction that increases the overall length of the actuator 10. Retraction

cylinder port 30 is disposed in the cylinder such that when a working fluid is introduced into the actuator through this port, it causes the piston assembly to move into the cylinder, or retract, thereby reducing the overall length of actuator 10. When the working fluid is removed from retraction cylinder port 30, rod 24 extends farther outside the cylinder, increasing the overall length of actuator 10.

The cylinder and piston assembly collectively define two internal cavities separated by the piston into which fluid may be introduced or removed. Extension cavity 32, when filled through port 28 causes the piston assembly to extend, increasing the overall length of the actuator. At the same time, retraction cavity 34 is emptied. Similarly, when retraction cavity 34 is filled, through retraction cylinder port 30, retraction cavity 34 fills with fluid, extension cavity 32 empties fluid through extension cylinder port 28.

Excluding the effects due to the size of piston rod 24, actuator 10 has a predetermined internal fluid volume that does not change based upon the position of the piston. This volume (again, discarding the effects due to the size of piston rod 24) is equal to the sum of the volumes of extension cavity 32 and retraction cavity 34.

Actuator 10 also includes a laser diode array 36 which includes one or more laser diodes, each of the laser diodes being configured to generate a laser light beam at a wavelength different from the other laser diodes in the array. These laser diodes are optically coupled to end cap 18 and are disposed with respect to the cylinder such that any of the laser diodes can generate laser beam 44. Cylinder 12 also includes an optical coupler or path 46 that is preferably disposed in one of the end caps (here shown in cap 18) to conduct the laser beam generated by one or more of laser diodes 38 from outside the cylinder to inside the cylinder. Cylinder 12 also includes a second optical coupler or path 48 that is similarly preferably mounted in or on one of the end caps of cylinder 12 (shown here as end cap 18) to conduct the laser beam 44 from a location inside the cylinder to a location outside the cylinder.

Optical couplers 46 and 48 are disposed such that laser beam 44 travels through cylinder 12 in a direction substantially parallel to the longitudinal axis 45 of the cylinder. The light impinges upon reflective surface 26, bounces back to

reflective surface 50, returns to reflective surface 26 on the piston and bounces off that surface to ultimately impinge upon the one or more photo diodes that make up photo diode array 40. The photo diodes, in turn, generate an electrical signal indicative of the light they received from laser beam 44.

Laser beam 44 is made of a series of pulses of light generated by the laser diodes. These pulses, when received by the photo diodes of array 40, cause the photo diodes to generate a similar pulse of electricity. Using actuator 10, one can determine the location of piston 22 within cylinder 12 by determining the time-of-flight of an individual laser pulse. By determining the time difference between when the pulse was created at the laser diodes and the time it was received and converted into an electrical signal by the photo diodes, i.e. the "time of flight", one can calculate the distance traveled by laser beam 44. This distance, as is clear in FIGURE 1, is a function of the displacement of piston 22 in cylinder 12.

In the embodiment of FIGURE 1, the light pulses generated by the laser diodes are generated in response to electrical signals provided by control unit 39. In addition, the electrical pulses generated by photodiode array 40 are transmitted to control unit 39. The control unit is coupled to laser diode array 36 by cable 37 which is coupled to both the control unit and the laser diode array. In a similar fashion, photo diode array 40 is electrically coupled to control unit 39 by cable 41. It is control unit 39 that determines the time-of-flight through actuator 10 by generating an electrical pulse which it then applies to cable 37 and by receiving a responsive electrical pulse on cable 41. The electrical pulse on cable 41 is generated by photo diode array 40 when it receives a pulse from laser beam 44.

By comparing the time difference between the moment a pulse was applied on cable 37 to the moment a responsive pulse was received on cable 41, control unit 39 can determine the time-of-flight, and hence, the position of piston 22 within cylinder 12. As actuator 10 extends or retracts, piston 22 moves in cylinder 12 and laser beam 44 changes in length. This change in length extends the path of laser beam 44, and thus increases the delay between the time an electrical pulse is generated and applied to cable 37 and the time a responsive pulse is received back at the control unit on

cable 41. This time delay is equivalent to the distance traveled by the electrical pulses in cable 37 and 41 in addition to the distance traveled by the light pulses along the path of laser beam 44. Thus, the delay time between the transmission of the pulse and the receipt of a responsive pulse is linearly related to the position of piston 22 and hence the extension of actuator 10.

Details of the structural control unit 39, and several ways of extracting a value indicative of the position of piston 22 within cylinder 12 can be found in U.S. Patent No. 5,517,198 which is incorporated herein by reference for all that it teaches, including the references cited therein, for all that they teach.

In the preferred embodiment, the laser beam will bounce off both the piston and a fixed surface to define a laser beam path that is substantially equal to four times the length of extension cavity 32. Alternatively, the laser beam need reflect only one time off reflective surface 26 and immediately return to the diodes of diode array 40.

In the arrangement shown in FIGURE 1, the laser beam travels in extension cavity 32. The laser diodes, photo diode array, laser beam and reflective surfaces could as easily have been disposed on end cap 16 to travel in retraction cavity 34.

The laser diodes 38 are preferably wave division multiplexed in operation. In addition, to help resolve the time-of-flight for single and multiple reflections, a triangle wave may be used as an analog reference and compared with a reference and delayed pulses.

If the working fluid of the cylinder is air, the attenuation of each pulse in laser beam 44 is insignificant. In this case, a single discrete wavelength is sufficient to get enough reflective intensity to generate a sufficient electrical signal at photo diodes 42. In such cases, a single laser diode and a single photo diode may be sufficient for all operating conditions. However, if the working fluid is a liquid, such as hydraulic oil, it may change its optical properties, such as refractive index, viscosity color and contamination over a period of time. To compensate for these changes in the working fluid, more than one laser diode and/or more than one photo diode may be required in laser diode array 36 and photo diode array 40, respectively.

In order to compensate for these changes in the fluid media, one or more laser diodes transmitting in the optical band from 430 nanometers to 1300 nanometers are preferred. The particular spacing of the frequencies of the laser diodes and the specific frequencies within this range will depend, of course, upon the specific working liquid used. For example, many hydraulic liquids that could be used in actuator 10 vary from golden to reddish to dark brown. In addition, some of these fluids may be contaminated with fluorescent dies from residual contaminates in the hydraulic lines and reservoirs. By providing a plurality of laser diodes operating at two or more frequencies, or by providing a tunable laser diode that is capable of operating at two or more frequencies, these frequencies may be scanned until a specific frequency is found that provides a sufficiently large electrical signal from one or more of the photodiodes in photodiode array 40.

Referring to FIGURE 2, a second embodiment of a linear actuator is shown. The difference between the actuator of FIGURE 1 and that of FIGURE 2 is the location of the photodiode array 40 and the laser diode array 36. In FIGURE 1, the two arrays are coupled to the end of actuator 10. Cables 37 and 41 have electrical conductors that electrically couple control unit 39 to the two arrays 36, 40. In the embodiment of FIGURE 2, the two arrays 36, 40 are disposed adjacent to the control unit (indeed, they may be in the same housing as the control unit, and cables 37' and 41' include fiber optic channels that conduct laser beam 44 to and from actuator 10. In all other respects the two systems are the same.

FIGURE 3 provides additional details of the embodiment of FIGURE 2 in the region of end cap 18. In FIGURE 2, optical coupler 46 is shown as a hermetically sealed fiber optic feed-through or connector. The free end of coupler 46 includes an adjustable focal length plano-convex lens 50 that is fixed to a screw-on end cap 52. The end cap is in threaded engagement with mating threads 54 on the outside surface of the barrel of optical coupler 46. By threading or un-threading this lens cap, and hence lens 50, the focal length of laser beam 44 can be adjusted to vary the intensity at the photo diode. Similarly, optical coupler 48 includes an adjustable focal length plano-convex lens 56 that is fixed to another screw-on end cap 58 which is threadedly engaged with mating threads 60 on the outer surface of the barrel of coupler 48.

Again, by varying the threaded engagement of the end cap with respect to the barrel, lens 56 can be moved toward or away from end cap 18 and the focal length of the laser beam 44 varied. This is done in order to optimize the magnitude of the electric signal coming from photo diode 42. Photo diode 42 is part of the photodiode array 40.

Each optical coupler, 46, 48 extends through end wall 18 and is coupled to a multi-mode fiber optic cable 37', 41', respectively. Couplers 46, 48 hold their respective fiber optic cables in alignment with respect to lens 50, 56, respectively. In this manner, laser beam 44 can travel down input fiber optic cable 37', through coupler 46, bounce off reflective surface 26 (FIGURE 1) and return to optical coupler 48, either directly or with an intermediate reflection off end cap 18, thence through output fiber optic cable 41', to photo diode/s 42. For convenience in FIGURE 2, only a single laser diode and a single photo diode is shown. More than one laser diode or photo diode can be used, as better shown in FIGURE 1. At the end of cables 37', 41' disposed away from cylinder 12, are collimators, 66, 68, for collimating laser beam 44. These collimators, here shown in exploded arrangement, preferably include an aspheric plano-convex lens. Input collimator 66 and output collimator 68 are preferably coupled to the end of cables 37' and 41', respectively, using SMA connectors 70, 72, and are held fixed with respect to laser diode 74 (or diode array, see FIGURE 1) and photo diode 42. A single laser diode and photo diode are shown in FIGURE 3. More than one of each may be used, however. By removing the light emitter (the laser diode) and the light receiver (the photo diode) from the vicinity of the cylinder, the emitter and detector can be spaced closely together and adjacent to circuitry for generating laser beam 44. By locating them closely together, such as is shown in FIGURE 3, by placing the laser diodes and photo diode in control unit 39 itself, the system as a whole will be better shielded from electromagnetic interference. This arrangement will also reduce parasitic capacitances and resistances which would make the accurate calculation of the piston position impossible.

The scope of this application is not to be limited by the description above, but is to be limited solely by the scope of the claims which follow.

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WHAT IS CLAIMED IS:

1. A fluid actuated cylindrical actuator, comprising:

a cylinder having first and second ends;

an end cap fixed to the first end of the cylinder and having a rod opening;

a piston disposed in the cylinder;

a rod coupled to the piston and extending from inside the cylinder to outside the cylinder and passing through the rod opening;

a first light guide extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder and to bar the passage of the fluid; and

a second light guide extending from inside the cylinder to outside the cylinder and adapted to transmit the at least a first beam of laser light at said first frequency from inside the cylinder to outside the cylinder and to bar the passage of the fluid.

2. The actuator of Claim 1, wherein the first light guide is disposed to transmit said first beam of laser light substantially along a longitudinal axis of the cylinder such that the first beam impinges upon a reflective portion of the piston over substantially an entire range of piston travel.

3. The actuator of Claim 2, wherein the second light guide is disposed to receive the first beam after it has been reflected off the piston.

4. The actuator of Claim 3, wherein the optical distance between the first light guide and the second light guide is a function of the degree of extension of the rod outside of the cylinder.

5. The actuator of Claim 4, wherein the first beam of light is reflected off a first surface inside the cylinder, wherein the first surface is coupled to the rod and configured to move with the rod.

6. The actuator of Claim 5, wherein the first beam of light is reflected off a second surface fixed with respect to the cylinder and moveable with respect to the rod, and a third surface fixed with respect to the rod and moveable with respect to the cylinder.

7. The actuator of Claim 6, wherein the first beam varies in optical length when the rod is moved with respect to the cylinder an amount equal to at least four times an axial distance the rod travels.

8. A hydraulic actuator for an agricultural or construction vehicle, the actuator comprising:

a) a cylinder having a substantially circular inner diameter and a longitudinal cylindrical axis;

b) a piston having a substantially circular outer diameter configured to be received in and hydraulically sealed against the inner diameter of the cylinder;

c) a piston rod with a substantially circular outer rod diameter, that is fixed to the piston and extends from the piston inside the cylinder, through a first end wall of the cylinder to a location outside the cylinder, wherein the first end wall is disposed to enclose and seal a first end of the cylinder and is substantially perpendicular to the longitudinal axis of the cylinder;

d) a second end wall fixed to the cylinder substantially perpendicular to the longitudinal axis of the cylinder and disposed to seal a second end of the cylinder, the second end wall including a first optical path configured to transmit a beam of laser light through the second end wall to a reflective surface fixed

to the piston and further including a second optical path configured to transmit the reflected beam of laser light back through the end wall;

e) a first optical fiber optically and mechanically coupled to the second end wall to transmit the beam of laser light from a remote laser light source to the first optical path; and

f) a second optical fiber optically and mechanically coupled to the second end wall to transmit the reflected beam of laser light to a remote laser light receiver.

9. The hydraulic actuator of Claim 8, wherein the first and second optical paths include at least one hermetically sealed fiber optic feed-through or connector extending through the second end wall.

10. The hydraulic actuator of Claim 9, wherein the at least one fiber optic feed-through or connector includes an adjustable focal length lens disposed in the beam of laser light and configured to adjust a focal length of the beam of laser light within the cylinder.

11. The hydraulic actuator of Claim 10, wherein the at least one fiber optic feed-through or connector includes a threaded end cap and further wherein the adjustable focal length lens is fixed to the end cap.

12. The hydraulic actuator of Claim 9 further comprising another hermetically sealed fiber optic feed-through or connector extending through the second end wall.

13. The hydraulic actuator of Claim 12, wherein the first and second optical fibers are multi-modal optical fibers.

14. The hydraulic actuator of Claim 13, further comprising a first laser diode configured to emit the beam of laser light at a wavelength in the range of 840 to 980 nanometers.

15. The hydraulic actuator of Claim 14, further comprising a first photo-diode configured to receive the beam of reflected laser light and generate an electrical signal indicative of at least one characteristic of the beam.

16. The hydraulic actuator of Claim 15, further comprising a second laser diode configured to emit the beam of laser light in the range of 430 to 1300 nanometers.

17. The hydraulic actuator of Claim 16, further comprising a second photo-diode configured to receive the beam of laser light and generate an electrical signal indicative of at least one characteristic of the beam.

18. A method of determining the position of the piston of the hydraulic actuator of Claim 8, comprising the steps of:

a) generating the beam of laser light;

b) reflecting the beam of laser light off a surface fixed to move axially with the piston;

c) receiving the reflected beam of laser light;

d) calculating a time of flight.

19. The method of Claim 18, wherein the step of generating the beam includes the step of generating the beam with a wavelength of between 430 and 1300 nanometers.

20. The method of Claim 19, wherein the step of generating the beam includes the step of generating the beam with a wavelength in the range of 840 and 980 nanometers.

21. The method of Claim 18, wherein the step of generating the beam includes the step of generating a sequence of individual pulses of light, and wherein the step of calculating a time of flight includes the step of determining the time of flight of at least one pulse in the sequence of individual pulses of light.

## ABSTRACT OF THE DISCLOSURE

A hydraulic actuator is disclosed having a cylinder with a piston that is moved by hydraulic fluid. A light guide in one end of the cylinder directs a laser beam into the cylinder, and off the piston where the beam is reflected. The beam then exits the cylinder through a second light guide. A control unit measures the time of flight of the laser beam and calculates the piston position.

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# MULTI-FIBER MULTI-CYLINDER POSITION METHOD AND APPARATUS USING TIME-OF-FLIGHT TECHNIQUE

## FIELD OF THE INVENTION

**[0001]** The invention relates generally to position sensing of hydraulic and pneumatic actuators. More particularly, it relates to sensing using laser light sources and detectors and determining the position of the actuator using time-of-flight algorithms.

## BACKGROUND OF THE INVENTION

**[0002]** Position sensing for hydraulic or pneumatic actuators typically uses an external position sensor, such as a rotary rheostat or potentiometer. Alternatively, linear rheostats or variable differential transformers are employed. These systems suffer from poor accuracy, extensive wear, and fragility in many applications, especially demanding applications such as their use on work and agricultural vehicles.

**[0003]** These sensors are quite susceptibly to damage, and suffer from being damaged during vehicle operation, or from the extremes in temperature that work and agricultural vehicles face.

**[0004]** In an effort to solve these problems, new methods of measuring the position of a hydraulic or pneumatic actuator have been devised that use microwaves. These waves are transmitted from one end of the cylinder, reflect off the piston, and return to a detector. By measuring the time-of-flight of these waves, the location of the piston can be determined.

Such an example is shown in U.S. Patent No. 6,005,395, which is incorporated herein by reference for all that it teaches.

[0005] The microwave transmitter suffers from high cost and difficulties in determining which of the many reflections in the cylinder is the proper one to measure.

[0006] In an alternative system, the pulse generating and timing circuits of patent application number 6,005,395 are used, but are coupled to a laser light source and respond to a reflection of that beam against a laser light detector, such as that shown in co-pending U.S. patent application serial number 09/750,866.

[0007] This arrangement also has drawbacks. When the piston moves toward or away from the source and detector, the reflected light follows multiple paths that, like the microwave transmitter and receiver pair, make the reflected pulses difficult to interpret. It is difficult to extract a good pulse indicative the precise time-of-flight of the laser beam.

[0008] An improvement on this system is provided in our co-pending application entitled "MULTI-FIBER CYLINDER POSITION SENSOR USING TIME-OF-FLIGHT TECHNIQUE", docket number 13936 and filed contemporaneously herewith. In that application, a single optical fiber transmits laser-light pulses from outside a hydraulic or pneumatic cylinder to inside the cylinder. The fiber is preferably located along a central longitudinal axis of the cylinder. The light pulses from the transmitting fiber travel down the cylinder substantially parallel to the longitudinal axis of the cylinder and reflect off the face of the piston in the cylinder. The light is reflected straight back toward the transmitting fiber. The path it follows in returning to the transmitting fiber at the end of the cylinder is substantially the same path as the path it traveled when going from the fiber to the piston. In short, the laser beam is preferably normal to the piston where it is reflected in order to provide these parallel in and out paths. When the laser light pulses return to the region of the transmitting fiber, they fall on the free ends of several optical fibers disposed around the central transmitting fiber. All of these fibers receive the light pulses at substantially the same time and conduct the light pulse from inside the cylinder to outside the cylinder. The

receiving fibers are closely spaced in a circular arrangement equidistant from the central fiber. Since the light pulse from the central fiber follows the same path back after reflecting from the piston, each of the fibers receives approximately the same amount of light energy, and receives it at almost exactly the same time.

**[0009]** The distal ends of the receiving fibers are coupled together such that each portion of the reflected light pulse that each individual fiber of the receiving fiber carries are merged to form a much stronger light pulse. The lengths of the receiving optical fibers are chosen such that the portions of the reflected light pulse that each one carries is merged into a single pulse at exactly the same time. This sharply increases the magnitude of the resulting pulse and provides an extremely fast and sharp rise time. In this manner, a reflected light pulse can be "reassembled" with a very sharp leading edge that permits precise time-of-flight measurements.

**[0010]** The system described in the foregoing patent application, however, discloses a separate laser diode and separate photodiode for use with a single cylinder. In addition, there is complex and expensive circuitry to expand the light pulse and compare the phases of the transmit and receive pulses to determine the time-of-flight in a cylinder, and thereby the position of the piston within the cylinder.

**[0011]** Duplicating this structure in a vehicle that has several hydraulic or pneumatic cylinders would be prohibitively expensive. Multiplying the arrangement of the 13936 application would require as many laser diodes, photodiodes, amplifier circuits, pulse expansion circuits and phase comparators as there are individual cylinders. What is needed, therefore, is a system that can measure the position of several hydraulic cylinders, yet does not require duplicate sets of circuitry for each of those cylinders. It is an object of this invention to provide such a system.

## SUMMARY OF THE INVENTION

[0012] In accordance with a first embodiment of the invention, a multiple cylinder position sensing system is provided that includes a first cylinder including a first source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the first beam of laser light that is reflected off the inside of the first cylinder, and a second cylinder including a second source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a second beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one second reflected light guide having a first end and a second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the second beam of laser light that is reflected off the inside of the second cylinder.

[0013] The system may include a laser light source that is optically coupled to the distal ends of both the first and second source light guides, and configured to generate a source beam of laser light, wherein the source beam is divided into the first and second beams of laser light. The system may include a first photodiode configured to receive and electrically respond to light from the first beam of laser light that is reflected off the inside of the first cylinder from the first reflected light guide. The system may also include a laser light source driver circuit coupled to the laser light source and configured to energize the laser light source upon receipt of a trigger pulse, and a timing circuit coupled to the laser light source driver configured to generate the trigger pulse and apply the trigger pulse to the laser light source driver circuit. The laser light source may be a laser diode. The system may include

first and second photodiode amplifiers that are coupled to the first and second photodiodes, respectively.

[0014] Each of the first and second photodiode amplifiers may be configured to generate an output signal.

[0015] The system may also include a pulse expansion circuit, to which the first and second photodiode output signals are coupled.

[0016] The second ends of the plurality of second light guides may be optically coupled to a single light detector. The light detector may have an electrical output that is produced by light carried by at least two of the plurality of second light guides.

[0017] In accordance with a second embodiment of the invention, a method for determining the time-of-flight of laser light pulses in a plurality of hydraulic or pneumatic cylinders is provided, including the steps of generating a timing pulse in a timing circuit, conducting the timing pulse to a laser light source and responsively generating laser light pulse from the source, conducting a first portion of the pulse through a first optical fiber to a first cylinder, conducting the first portion into the first cylinder, reflecting the first portion off a first reflective surface coupled to a first piston in the first cylinder, receiving the first portion at a first photo diode and responsively generating a first electrical signal, conducting a second portion of the pulse through a second optical fiber to a second cylinder, conducting the second portion into the second cylinder, reflecting a second portion off a second reflective surface coupled to a second piston in the second cylinder, receiving the second portion at a second photo diode and suppressing the generation of the second electrical signal, providing the first electrical signal and the timing pulse to a comparator circuit and responsibly generating a first output signal indicative of a first time difference between the arrival of the timing pulse and the arrival of the first electrical signal at the comparator circuit.

[0018] The method may also include the steps of generating a second timing pulse in the timing circuit, conducting the second pulse to the laser light source and responsibly

generating a second laser light pulse from the source, conducting a first portion of the second laser light pulse through the first optical fiber to the first cylinder, conducting the first portion of the second laser light pulse into the first cylinder, reflecting the first portion of the second laser light pulse off the first reflective surface, receiving the first portion of the second laser light pulse at the first photo diode and suppressing the generation of a third electrical signal indicative of the time of arrival of the first portion of the second laser light pulse at the first photo diode, conducting a second portion of the second laser light pulse through the second optical fiber to the second cylinder, conducting the second portion of the second laser light pulse into the second cylinder, reflecting the second portion of the second laser light pulse off the second reflective surface, receiving the second portion of the second laser light pulse at a second photo diode and responsibly generating a fourth electrical signal indicative of the time of arrival of the second portion of the second laser light pulse at the second photo diode, providing the fourth electrical signal in the second timing pulse to the comparator circuit and responsibly generating a second output signal indicative of a second time difference between the arrival of the timing pulse and the second electrical signal at the comparator circuit.

[0019] The step of conducting the first timing pulse to the laser light source and responsively generating a second laser light pulse from the source may include the steps of optically coupling the laser light source to distal ends of the first and second optical fibers, and dividing the first laser light pulse into the first and second portions. The method may also include the steps of providing a laser light source driver circuit, coupling the laser light source to the driver circuit, applying the first and second timing pulses to the laser light source driver circuit, and energizing the laser light source responsive to the application of the first and second timing pulses to the driver circuit. The method may include the steps of providing a first photo diode amplifier and coupling the first photo diode amplifier to the first photo diode, providing a second photo diode amplifier and coupling the second photo diode amplifier to the second photo diode, generating a first gate signal in the timing circuit, applying the first gate signal to the first photo diode amplifier to permit the transmission of first electrical signal, generating a second gate signal in the timing circuit, and applying the second gate signal to the second photo diode amplifier to suppress the transmission of the

second electrical signal. The method may include the step of configuring the first and second photo diode amplifiers to generate first and second amplifier output signals, respectively. The method may include the step of coupling the first and second photo diode amplifier output signals and transmitting the coupled output signals to a pulse expansion circuit. The method may include the step of transmitting the first and second output signals to a pulse expansion circuit. The method may include the steps of generating an expanded pulse output signal in the pulse expansion circuit, and outputting the expanded pulse output signal from the pulse expansion circuit. The method may include the steps of providing a pulse comparator circuit, and inputting the expanded pulse output signal and the timing pulse into the pulse comparator circuit, and generating a time delay output signal in the pulse comparator circuit indicative of a time delay between the timing pulse and the expanded pulse output signal.

**[0020]** In accordance with a third embodiment of the invention, a method of determining the time-of-flight of laser light in a plurality of hydraulic or pneumatic cylinders includes the steps of transmitting a laser light pulse from a laser diode, dividing the laser light pulse into at least first and second sub-pulses, injecting the first and second sub-pulses into first and second cylinders, respectively, reflecting the first and second sub-pulses off first and second pistons in the first and second cylinders, respectively, transmitting the first and second reflected sub-pulses at two first and second photo diodes, respectively, generating first and second electrical signals in the first and second photo diodes that are indicative of the first and second times of arrival of the first and second sub-pulses at the first and second photo diodes, respectively, selectively coupling the first and second electrical signals in a first mode of operation to a pulse expansion circuit and a phase comparator circuit to generate a first time-of-flight signal on an output line of the phase comparator circuit that is indicative of the time-of-flight of the first sub-pulse and not of the second sub-pulse, repeating the foregoing steps with a second pulse of laser light, but in a second mode of operation wherein the phase comparator circuit generates a second time-of-flight signal on the output line that is indicative of the time-of-flight of the second sub-pulse and not of the first sub-pulse of the second pulse of laser light.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The present invention will become more fully understood from the following detailed description, taken in conjunction with the accompanying drawings, wherein like reference numerals refer to like parts, in which:

[0022] FIGURE 1 is a partial cross-sectional view of a hydraulic actuator having the laser-based reflective beam sensor and a control unit for generating the laser beam and calculating the position of the actuator wherein the laser light sources are located remotely from the actuator and cables including three fiber optic light guides couple the control unit to the actuator;

[0023] FIGURE 2 is a partial cross-sectional view of the embodiment of FIGURE 1 showing how the light guides are coupled to the cylinder;

[0024] FIGURE 3 is graph of laser light transmissivities through several different hydraulic fluids of various ages and types; and

[0025] FIGURE 4 illustrates an arrangement that includes several cylinders that are multiplexed together sharing common circuitry in accordance with the present invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0026] FIGURE 1 is a schematic view of a linear cylindrical actuator 10 in accordance with the present invention. Actuator 10 includes a cylinder 12 having an inner diameter 14 and two end caps 16, 18. Rod end cap 16 encloses one longitudinal end of the cylinder and has an opening 17 through which rod 24 passes. Opening 17 seals against the surface of the rod and prevents actuating fluid from leaking out. End cap 18 encloses the opposing end of the cylindrical potion of the cylinder and prevents actuating fluid from leaking out.

[0027] Actuator 10 also includes a piston assembly 20 which includes a piston 22 having an outside diameter 23 configured to seal against the inner diameter 14 of the cylinder and to slide longitudinally, back and forth, with respect to cylinder 12. Piston 22 is coupled to rod

24, which extends from the inside of the cylinder to the outside of the cylinder through opening 17 and is fixed to piston 22 to move simultaneously with the piston. Surface 26 is a reflective surface fixed to move with piston 22 and is configured to reflect laser light that is introduced into the cylinder. Two ports 28, 30 are provided in the cylinder to introduce an operating fluid into the cylinder or remove the operating fluid from the cylinder. Extension cylinder port 28 is disposed in the cylinder such that fluid introduced into the port will cause the piston and piston rod to move in a direction that increases the overall length of the actuator 10. Retraction cylinder port 30 is disposed in the cylinder such that when a working fluid is introduced into the actuator through this port, it causes the piston assembly to move into the cylinder, or retract, thereby reducing the overall length of actuator 10. When the working fluid is removed from retraction cylinder port 30, rod 24 extends farther outside the cylinder, increasing the overall length of actuator 10.

[0028] The cylinder and piston assembly collectively define two internal cavities separated by the piston into which fluid may be introduced or removed. Extension cavity 32, when filled (through port 28) causes the piston assembly to extend, increasing the overall length of the actuator. At the same time, retraction cavity 34 is emptied. Similarly, when retraction cavity 34 is filled, through retraction cylinder port 30, retraction cavity 34 fills with fluid, extension cavity 32 empties fluid through extension cylinder port 28.

[0029] Excluding the effects due to the size of piston rod 24, actuator 10 has a predetermined internal fluid volume that does not change based upon the position of the piston. This volume (again, discarding the effects due to the size of piston rod 24) is equal to the sum of the volumes of extension cavity 32 and retraction cavity 34.

[0030] An optical coupler 34 is fixed in end cap 18 to communicate laser light into chamber 32 and to communicate laser light from chamber 32 outside the cylinder. The cap itself has a threaded external surface that engages mating threads in end cap 18. These threads serve to secure the coupler to the end cap and to prevent leakage of hydraulic fluid or air out of the cylinder. The coupler also serves to hold several optical fibers 36, 38 in a fixed relationship with respect to cylinder 12. Coupler 34 is preferably disposed along the

centerline of cylinder 12 such that the cylinder and the coupler share a common cylindrical axis 40. Referring now to FIGURE 2, coupler 34 supports eight optical fibers ranged in arcuate, preferably circular, pattern equidistantly spaced from the longitudinal cylindrical axis of the coupler. These fibers gather light that is reflected off surface 26 and conduct it out of the cylinder. Fiber 36 is disposed along axis 40 and conducts light from outside the cylinder into the cylinder. Light that is conducted into the cylinder through fiber 36 is directed towards reflective surface 26 on piston 22. It reflects off piston 22 and returns in a plurality of paths to each of optical fibers 28. These fibers receive the light at substantially the same time and conduct the light out of the cylinder. An optical multiplexer 42 is optically coupled to fibers 38 and joins their/there individual light beams into a single beam that exits multiplexer 42 in optical fiber 44. Thus, the light carried by optical coupler 44 is the combination of all the individual beams of light carried by optical fibers 38.

[0031] Referring now to FIGURE 1, optical fiber 44 is at its other end connected to optical coupler 46, which directs and focuses the light beam of fiber 44 to photodiode 48. When the light passes through coupler 46 and falls upon photodiode 48, it changes the conductivity of the photodiode causing a change in the current flowing through circuit 50. This change in current, or photodiode signal, is amplified by photodiode amplifier 52. The output of photodiode amplifier 52 is fed to pulse expansion circuit 54 which increases the width of the photodiode signal. Phase comparison circuit 56 receives two impulses: the expanded pulse from pulse expansion circuit 54 and a trigger pulse from timing circuit 58. By determining the time difference between the pulse of timing circuit 58 and the expanded pulse from circuit 54, phase comparison circuit 56 generates a signal indicative of the time delay between these two pulses. This time delay signal is output signal 60.

[0032] Timing circuit 58 generates periodic pulses on the order of once every tenth of a second. These two pulses are provided on two signal lines. Signal line 62, which goes to phase comparison circuit 56 and signal line 64, which goes to laser driver circuit 66. Laser driver circuit 66, when it receives this timing signal, generates a pulse that is applied to laser diode 68. Laser diode 68 turns the signal into a laser light pulse, which is transmitted through optical fiber 36 and coupler 34 into cylinder 12. The laser light pulse traverses

cavity 32, reflects off surface 26 and returns to optical fibers 38, which are held in coupler 34.

[0033] Referring back to phase comparison circuit 56, circuit 56 receives a pulse on line 62 generated by timing circuit 58. It also receives an expanded pulse from pulse expansion circuit 54. The difference in time of arrival of these two pulses is substantially equal to the amount of time it takes for the laser light pulse to travel from laser diode 68 to photodiode 48. Whenever piston 20 moves, both the path from laser diode 68 to the piston increases and the path from the piston to photodiode 48 increases. Since this is a linear device, for every inch of movement of piston 20 the path length changes by two inches.

[0034] Pulse expansion circuit 54 is disclosed in more detail in U.S. Patent No. 6,005,395 as the directional sampler 74. The output of pulse expansion circuit 54 is an equivalent-time replica of the reflected pulses received by photodiode 48.

[0035] Phase comparison circuit 56 is described in U.S. Patent No. 6,005,395 as directional set/reset circuit 100.

[0036] The output signal 60 is preferably in the form of a square wave having a pulse width indicative of the time required for the light emitted from laser diode 68 to travel through the system. Changes in the pulse width are preferably proportional to the distance the piston has traveled.

[0037] Referring now to FIGURE 2, we see a cross-section of the end of actuator 10 taken at Section 2-2 in FIGURE 1. The coupler 34 is fixed to optical fibers 38 that transmit the reflected light beam out of the cylinder. In the embodiment shown, there are eight optical fibers arranged in a circular pattern about optical fiber 36, which is also supported in coupler 34. Coupler 34 is preferably disposed within the cylinder, as shown in FIGURE 2, such that fiber 38 enters the cylinder substantially coaxial with longitudinal axis 40 of the cylinder. Each of the eight fibers 38 is preferably disposed equidistantly with respect to fiber 38 and is preferably spaced equidistantly apart from the others of fibers 38. In this manner, each fiber

has a corresponding fiber disposed on the opposing side of optical fiber 38 from which they are both equally spaced.

[0038] In addition, the longitudinal axis of each of the optical fibers 38 and optical fiber 36 are preferably parallel such that light transmitted into the cylinder through optical fiber 38 will reflect off surface 26 of piston 20 and return directly to coupler 34. If surface 26 is disposed in a substantially perpendicular orientation with respect to the longitudinal axes of fibers 38 and 36, substantially all the light that is emitted into cylinder 12 by optical fiber 38 will arrive back at coupler 34.

[0039] The benefit of having several optical fibers for receiving reflected light is two fold. First, a smaller diameter optical fiber can be spaced closer to fiber 36. This closer spacing means that it is in a better position to receive the reflected light that reflects off perpendicular reflective surface 26. Secondly, by providing several optical fibers, considerably more reflected light can be gathered and provided to photodiode 48. This provides a substantially larger pulse and reduces any the possibility that stray reflections will trigger photodiode 48.

[0040] To provide this additive effect, each of optical fibers 38 is preferably the same length. Thus, when reflected light is received substantially simultaneously at each of the end of optical fibers 38 in cylinder 12, these pulses will take substantially the same time to arrive at multiplexer 42. Since each of fibers 38 are multiplexed together, the light in each fiber 38 will be added and inserted into optical fiber 44. Thus, any reflected light falling simultaneously on the receiving ends of fibers 38 will be combined and arrive simultaneously at the photodiode.

[0041] The spacing between fiber 36 and each of fiber 38 is preferably small, on the order of one to two centimeters. More preferably it is between five and ten millimeters.

[0042] FIGURE 3 is a plot of transmissivity vs. wavelength. It measures the degree to which laser light is attenuated as it passes through hydraulic fluids of varying types. The types of hydraulic fluid tested include "J" type fluid with in-trained air, "J" type fluid, old "E" type fluid, old "F" type fluid, and old "G" type fluid as shown in the legend in FIGURE

3. These types of hydraulic fluid are well known to engineers working with hydraulic fluids, and represent several of the most common fluids used in hydraulic systems today. The "E", "F" and "G" type fluids are "old" in that the fluids tested have been used in actual hydraulic equipment, and were not new. Three of the four hydraulic fluids that make up the J, E, F and G fluids are Case hydraulic fluids MS 1207 Hi Tran Plus, MS 1209 Hi Tran Ultra, and MS 1230. The reason these fluids were chosen was to see the degree to which aging and use of a hydraulic fluid would cause the optical characteristics of such fluid to degrade. The assumption is that degraded or "old" fluid by its accumulation of moisture, oxygen, and suspended particulates such as metal particles would not transmit laser light as readily as new hydraulic fluids. The chart in FIGURE 3 indicates the qualities of each of the aforementioned fluids. Note that the transmission of light is restricted almost entirely in the range of 500 – 1700 nanometers. Outside this range, there is virtually no transmission of light. Within this range, however, there are three separate sub-ranges in which a significant amount of light is transmitted. These ranges are 700-1150 nanometers, 1250-1400 nanometers, and 1450-1650 nanometers. The broadest of these three ranges is the band between 700 and 1150 nanometers. In this range, there are three significant sub-ranges in which transmissivity is substantial these include the sub-range of 700-900 nanometers, 950-1025 nanometers, and 1030-1150 nanometers. Each of these sub-bands has a local transmissivity maximum at 850, 970, and 1090 nanometers, respectively. The other two major bands have their respective maxima at 1315 nanometers and 1560 nanometers, respectively.

[0043] Note that, in comparing each of the hydraulic fluids, the peak transmissivities in each of the bands and sub-bands do not vary substantially from the peak transmissivities of the other peak transmissivities. Comparing the "G_old" to the "E_old" fluids, although the variations in transmissivity at each of their respective maxima varies from .1 (at 1090 nanometers) to .4 (at 850 nanometers), the wavelengths of these respective maxima are the same.

[0044] Based upon this empirical analysis, it is clear that as hydraulic fluid ages its transmissivity peaks do not shift. An appropriate high power laser diode for transmitting

light through the hydraulic fluid would therefore be preferably selected to have a wavelength at or near any of the local maxima shown in FIGURE 3. As that oil ages, and in the absence of any maxima wavelength shift, one would expect the transmissivity to drop, but not to shift radically based upon wavelength. For this reason, a laser diode having a frequency of 850, +80/-125 nanometers, 970+/-30 nanometers, or 1090+/-30 nanometers would be particularly preferred. While the other two major bands also exhibit strong transmissivity at their local maxima, due to the sudden and extreme drop-off on either side of the local maxima there less preferred. Nonetheless, even though they are less preferred, a laser diode having a wavelength of 1325, +/- 50 nanometers, or 1560 +/- 50 nanometers would also be acceptable.

**[0045]** FIGURE 4 illustrates an arrangement of multiple hydraulic cylinders with laser light sensors that are connected to a single laser diode. This arrangement permits a plurality of hydraulic or pneumatic cylinders to be monitored by a single pulse expansion circuit and phase comparator circuit. There are similarities between the circuit of FIGURE 1 as well as differences. First, we would like to discuss the similarities. The cylinders 10 are identical both in FIGURE 1 and FIGURE 4. The optical couplers 34 are also identical in both FIGURE 1 and FIGURE 4. The optical fibers and connectors extending from the cylinder to the photodiode amplifier are also identical in both figures. Furthermore, the laser driver 66 and laser diode 68 are also identical. Optical fiber 37' in FIGURE 4 differs from optical fiber 37 in FIGURE 1 in that it includes at least three separable sub-fibers that are joined together at a distal end located away from the three hydraulic cylinders and adjacent to the laser diode such that each of the three is positioned to gather a portion of the light generated by the laser diode. At the other end, each of the separable sub-fibers are separated and directed to each of three fiber optic connectors 39. The other end of these three optical fibers are held closely together and disposed in the optical path in front of laser diode 68. In this manner, laser light generated by laser diode 68 is transmitted into at least three fibers at once.

**[0046]** When laser diode 68 generates a pulse of light, that pulse is transmitted into each of the three optical fibers that are closely coupled to the laser diode. Since the three fibers are separated and connected to individual fiber optic connectors 39, the pulse of light travels down each of the three fibers through connectors 39, through each of three optical fibers 36

and into all three hydraulic actuators 10. The light pulses traverse cylinder 12, reflect off reflective surface 26 and return to optical couplers 34. Each of the individual fibers 38 for each of the couplers 34 receives a portion of the light, which is then merged at multiplexers 42. For each of the three cylinders, the reflected pulse of laser light then travels down optical fiber 44, through collimating lens assembly 46 and falls upon photodiode 48.

**[0047]** Thus, the light from laser diode 68 is received at three different photodiodes and three different photodiode amplifiers. Each pulse of light from laser diode 68 is therefore first divided into three separate optical fibers. The three pulses from these three fibers are reflected off a piston and the reflected pulses are then further sub-divided into two or more receiving optical fibers 38. For each actuator, the reflected optical pulses that are gathered by two or more individual fibers 38 are gathered together again and converted into a single optical pulse (with a greater amplitude than any of the three sub-divided pulses on fibers 38) and is applied to a corresponding photo diode amplifier 52' for that actuator.

**[0048]** The output of each photodiode amplifier 52' is joined to the other outputs, which are provided to pulse expansion circuit 54. The expanded pulse is then transmitted to phase comparator 56, which then provides the time-of-flight on line 60 for further processing.

**[0049]** In practical application, it is anticipated that each of the three actuators 10 will operate independently of the other. As a result, one piston may be very close to optical coupler 34 while another piston is far away. As time progresses, the two pistons may move towards one another, cross paths, and assume the opposite orientation, with the extended cylinder now retracted and the retracted cylinder now extended.

**[0050]** If pulse expansion circuit 54 simultaneously received signals from all three photodiode amplifiers whenever a pulse of light was generated by laser diode 68, it would become impossible for it to differentiate between the three cylinders. If the optical path lengths for the three cylinders were ever equal, due to movement of pistons 20, photodiode amplifiers 52 prime would transmit pulses at the same time. As the optical paths change

their relative lengths, it would become impossible to determine, as they separated, which pulse received by pulse expansion circuit 54 corresponded to which cylinder.

**[0051]** For this reason, timing circuit 58' is equipped to not only generate simultaneous pulses on line 62 and 64 (the lines coupled to phase comparator circuit 56 and laser driver 66) respectively, but also to selectively enable a single photodiode amplifier 52' and disable the other photo diode amplifiers 52' using one or more of gate signals: gate 1, gate 2, or gate 3.

**[0052]** In the preferred embodiment, each of photodiode amplifiers 52' will not transmit a pulse to pulse expansion circuit 54 unless they receive a corresponding gate signal on their corresponding gate signal line. When they do not transmit a pulse, they are "disabled", and vice-versa. Thus, timing circuit 58' generates a gate pulse on one of the gate signal lines at substantially the same time as it generates the timing pulse on line 62 and 64. If the gate signal is transmitted on gate signal line "gate 1" then only the pulse of light returning from the top most cylinder in FIGURE 4 will be transmitted by a photodiode amplifier to the pulse expansion circuit. The other two photodiode amplifiers 52', not receiving a gate signal, will not transmit a corresponding signal indicating that they received reflected light to pulse expansion circuit 54. In this manner, timing circuit 58' can selectively enable or disable a plurality of photodiode amplifiers, thereby preventing the transmission of one or more reflected light pulses in electrical form to pulse expansion circuit 54.

**[0053]** While the embodiments illustrated in the FIGURES and described above are presently preferred, it should be understood that these embodiments are offered by way of example only. The invention is not intended to be limited to any particular embodiment, but is intended to extend to various modifications that nevertheless fall within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A multiple cylinder position sensing system is provided comprising:

a first cylinder including:

a first source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder; and

at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the first beam of laser light that is reflected off the inside of the first cylinder;

a second cylinder including:

a second source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a second beam of laser light at a first frequency from outside the cylinder to inside the cylinder; and

at least one second reflected light guide having a first end and a second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the second beam of laser light that is reflected off the inside of the second cylinder.

2. The system of Claim 1, further comprising a laser light source that is optically coupled to the distal ends of both the first and second source light guides, and configured to generate a source beam of laser light, wherein the source beam is divided into the first and second beams of laser light.

3. The system of Claim 2, further comprising a first photodiode configured to receive and electrically respond to light from the first beam of laser light that is reflected off the inside of the first cylinder from the first reflected light guide.

4. The system of Claim 3, further comprising:

a laser light source driver circuit coupled to the laser light source and configured to energize the laser light source upon receipt of a trigger pulse; and

a timing circuit coupled to the laser light source driver configured to generate the trigger pulse and apply the trigger pulse to the laser light source driver circuit.

5. The system of Claim 4, wherein the laser light source is a laser diode.

6. The system of Claim 5, further comprising first and second photodiode amplifiers that are coupled to the first and second photodiodes, respectively.

7. The system of Claim 6, wherein each of the first and second photodiode amplifiers is configured to generate an output signal.

8. The system of Claim 7, further comprising a pulse expansion circuit, wherein the first and second photodiode output signals are coupled to the pulse expansion circuit.

9. A method for determining the time-of-flight of laser light pulses in a plurality of hydraulic or pneumatic cylinders, the method including the steps of:

generating a first timing pulse in a timing circuit;

conducting the first timing pulse to a laser light source and responsively generating a first laser light pulse from the source;

conducting a first portion of the first laser light pulse through a first optical fiber to a first cylinder;

conducting the first portion of the first laser light pulse into the first cylinder;

reflecting the first portion off a first reflective surface coupled to a first piston in the first cylinder;

receiving the first portion of the first laser light pulse at a first photodiode and responsively generating a first electrical signal indicative of the time of arrival of the first portion of the first laser light pulse at the first photodiode;

conducting a second portion of the first laser light pulse through a second optical fiber to a second cylinder;

conducting the second portion of the first laser light pulse into the second cylinder;

reflecting the second portion of the first laser light pulse off a second reflective surface coupled to a second piston in the second cylinder;

receiving the second portion of the first laser light pulse at a second photodiode and suppressing the transmission of a second electrical signal indicative of the time of arrival of the second portion of the first laser light pulse at the second photodiode; and

providing the first electrical signal and the timing pulse to a comparator circuit and responsively generating a first output signal indicative of a first time difference between the arrival of the timing pulse and the arrival of the first electrical signal at the comparator circuit.

10. The method of Claim 9, further comprising the steps of:

generating a second timing pulse in the timing circuit;

conducting the second timing pulse to the laser light source and responsively generating a second laser light pulse from the source;

conducting a first portion of the second laser light pulse through the first optical fiber to the first cylinder;

conducting the first portion of the second laser light pulse into the first cylinder;

reflecting the first portion of the second laser light pulse off the first reflective surface;

receiving the first portion of the second laser light pulse at the first photodiode and suppressing the generation of a third electrical signal indicative of the time of arrival of the first portion of the second laser light pulse at the first photodiode;

conducting a second portion of the second laser light pulse through the second optical fiber to the second cylinder;

conducting the second portion of the second laser light pulse into the second cylinder;

reflecting the second portion of the second laser light pulse off the second reflective surface;

receiving the second portion of the second laser light pulse at a second photodiode and responsively generating a fourth electrical signal indicative of the time of arrival of the second portion of the second laser light pulse at the second photodiode; and

providing the fourth electrical signal and the second timing pulse to the comparator circuit and responsively generating a second output signal indicative of a second time difference between the arrival of the timing pulse and the second electrical signal at the comparator circuit.

11. The method of Claim 9, wherein the step of conducting the first timing pulse to the laser light source and responsively generating a second laser light pulse from the source includes the steps of:

optically coupling the laser light source to distal ends of the first and second optical fibers; and

dividing the first laser light pulse into the first and second portions.

12. The method of Claim 11, further comprising the steps of:

providing a laser light source driver circuit;

coupling the laser light source to the driver circuit;

applying the first and second timing pulses to the laser light source driver circuit; and

energizing the laser light source responsive to the application of the first and second timing pulses to the driver circuit.

13. The method of Claim 9, further comprising the steps of:

providing a first photodiode amplifier and coupling the first photodiode amplifier to the first photodiode;

providing a second photodiode amplifier and coupling the second photodiode amplifier to the second photodiode;

generating a first gate signal in the timing circuit;

applying the first gate signal to the first photodiode amplifier to permit the transmission of the first electrical signal;

generating a second gate signal in the timing circuit; and

applying the second gate signal to the second photodiode amplifier to suppress the transmission of the second electrical signal.

14. The method of Claim 13, further comprising the step of:

configuring the first and second photodiode amplifiers to generate first and second amplifier output signals, respectively.

15. The method of Claim 14, further comprising the step of:

coupling the first and second photodiode amplifier output signals; and

transmitting the coupled output signals to a pulse expansion circuit.

16. The method of Claim 14, further comprising the step of:

transmitting the first and second output signals to a pulse expansion circuit.

17. The method of Claim 16 further comprising the steps of:

generating an expanded pulse output signal in the pulse expansion circuit; and

outputting the expanded pulse output signal from the pulse expansion circuit.

18. The method of Claim 17, further comprising the steps of:

providing a pulse comparator circuit; and

inputting the expanded pulse output signal and the timing pulse into the pulse comparator circuit; and

generating a time delay output signal in the pulse comparator circuit indicative of a time delay between the timing pulse and the expanded pulse output signal.

19. A method of determining the time-of-flight of laser light in a plurality of hydraulic or pneumatic cylinders comprising the steps of:

transmitting a laser light pulse from a laser diode;

dividing the laser light pulse into at least first and second sub-pulses;

injecting the first and second sub-pulses into first and second cylinders, respectively;

reflecting the first and second sub-pulses off first and second pistons in the first and second cylinders, respectively;

receiving the first and second reflected sub-pulses to first and second photodiodes, respectively;

generating first and second electrical signals in the first and second photodiodes that are indicative of the first and second times of arrival of the first and second sub-pulses at the first and second photodiodes, respectively;

selectively coupling the first and second electrical signals in a first mode of operation to a pulse expansion circuit and a phase comparator circuit to generate a first time-of-flight signal on an output line of the phase comparator circuit that is indicative of the time-of-flight of the first sub-pulse and not of the second sub-pulse; and

repeating the foregoing steps with a second pulse of laser light but in a second mode of operation wherein the phase comparator circuit generates a second time-of-flight signal on the output line that is indicative of the time-of-flight of the second sub-pulse and not of the first sub-pulse of the second pulse of laser light.

## ABSTRACT OF THE DISCLOSURE

A hydraulic actuator is disclosed having a cylinder with a piston that is moved by hydraulic fluid. A laser diode emits a pulse or pulses of light that form laser light beam. These pulses are provided to two or more optical fibers that extend into two or more corresponding cylinders. For each of these cylinders, the optical fiber enters the cylinder at one end of the cylinder and directs a laser beam into the cylinder, and off the piston where the beam is reflected. The reflected beam then exits the cylinder through at least two corresponding optical fibers disposed on either side of the fiber that conducted the light into the cylinder. Each of the optical fibers that receives reflected light is joined together with the others of the optical fibers into one fiber that carries the reflected beam of light to a photo-diode located remote from the cylinder. Each of the photo diodes for each of the two or more cylinders has a corresponding photo diode amplifier. The output of these amplifiers are coupled together and provided to a pulse expansion circuit. The timing circuit that generates the pulse that triggers the laser diode also generates gate pulses for each of the photo diode amplifiers. These gate signals suppress the output of all but one of the photo diode amplifiers. In this manner, the pulse expansion circuit and phase comparator circuits that receive the photo diode amplifier signals will generate an output signal indicative of the time-of-flight of the laser light pulse in only one cylinder at a time. This permits the system to select a specific cylinder and generate a signal indicative of the position of the piston within the cylinder: the time-of-flight of the laser light pulse.

# MULTI-FIBER MULTI-CYLINDER POSITION METHOD AND APPARATUS USING TIME-OF-FLIGHT TECHNIQUE

## FIELD OF THE INVENTION

The invention relates generally to position sensing of hydraulic and pneumatic actuators. More particularly, it relates to sensing using laser light sources and detectors and determining the position of the actuator using time-of-flight algorithms.

## BACKGROUND OF THE INVENTION

Position sensing for hydraulic or pneumatic actuators typically uses an external position sensor, such as a rotary rheostat or potentiometer. Alternatively, linear rheostats or variable differential transformers are employed. These systems suffer from poor accuracy, extensive wear, and fragility in many applications, especially demanding applications such as their use on work and agricultural vehicles.

These sensors are quite susceptibly to damage, and suffer from being damaged during vehicle operation, or from the extremes in temperature that work and agricultural vehicles face.

In an effort to solve these problems, new methods of measuring the position of a hydraulic or pneumatic actuator have been devised that use microwaves. These waves are transmitted from one end of the cylinder, reflect off the piston, and return to a detector. By measuring the time-of-flight of these waves, the location of the piston can be determined.

Such an example is shown in U.S. Patent No. 6,005,395, which is incorporated herein by reference for all that it teaches.

The microwave transmitter suffers from high cost and difficulties in determining which of the many reflections in the cylinder is the proper one to measure.

In an alternative system, the pulse generating and timing circuits of patent application number 6,005,395 are used, but are coupled to a laser light source and respond to a reflection of that beam against a laser light detector, such as that shown in co-pending U.S. patent application serial number 09/750,866.

This arrangement also has drawbacks. When the piston moves toward or away from the source and detector, the reflected light follows multiple paths that, like the microwave transmitter and receiver pair, make the reflected pulses difficult to interpret. It is difficult to extract a good pulse indicative the precise time-of-flight of the laser beam.

An improvement on this system is provided in our co-pending application entitled "MULTI-FIBER CYLINDER POSITION SENSOR USING TIME-OF-FLIGHT TECHNIQUE", docket number 13936, and filed contemporaneously herewith. In that application, a single optical fiber transmits laser-light pulses from outside a hydraulic or pneumatic cylinder to inside the cylinder. The fiber is preferably located along a central longitudinal axis of the cylinder. The light pulses from the transmitting fiber travel down the cylinder substantially parallel to the longitudinal axis of the cylinder and reflect off the face of the piston in the cylinder. The light is reflected straight back toward the transmitting fiber. The path it follows in returning to the transmitting fiber at the end of the cylinder is substantially the same path as the path it traveled when going from the fiber to the piston. In short, the laser beam is preferably normal to the piston where it is reflected in order to provide these parallel in and out paths. When the laser light pulses return to the region of the transmitting fiber, they fall on the free ends of several optical fibers disposed around the central transmitting fiber. All of these fibers receive the light pulses at substantially the same time and conduct the light pulse from inside the cylinder to outside the cylinder. The

receiving fibers are closely spaced in a circular arrangement equidistant from the central fiber. Since the light pulse from the central fiber follows the same path back after reflecting from the piston, each of the fibers receives approximately the same amount of light energy, and receives it at almost exactly the same time.

The distal ends of the receiving fibers are coupled together such that each portion of the reflected light pulse that each individual fiber of the receiving fiber carries are merged to form a much stronger light pulse. The lengths of the receiving optical fibers are chosen such that the portions of the reflected light pulse that each one carries is merged into a single pulse at exactly the same time. This sharply increases the magnitude of the resulting pulse and provides an extremely fast and sharp rise time. In this manner, a reflected light pulse can be "reassembled" with a very sharp leading edge that permits precise time-of-flight measurements.

The system described in the foregoing patent application, however, discloses a separate laser diode and separate photodiode for use with a single cylinder. In addition, there is complex and expensive circuitry to expand the light pulse and compare the phases of the transmit and receive pulses to determine the time-of-flight in a cylinder, and thereby the position of the piston within the cylinder.

Duplicating this structure in a vehicle that has several hydraulic or pneumatic cylinders would be prohibitively expensive. Multiplying the arrangement of the 13936 application would require as many laser diodes, photodiodes, amplifier circuits, pulse expansion circuits and phase comparators as there are individual cylinders. What is needed, therefore, is a system that can measure the position of several hydraulic cylinders, yet does not require duplicate sets of circuitry for each of those cylinders. It is an object of this invention to provide such a system.

## SUMMARY OF THE INVENTION

In accordance with a first embodiment of the invention, a multiple cylinder position sensing system is provided that includes a first cylinder including a first source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the first beam of laser light that is reflected off the inside of the first cylinder, and a second cylinder including a second source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a second beam of laser light at a first frequency from outside the cylinder to inside the cylinder, and at least one second reflected light guide having a first end and a second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the second beam of laser light that is reflected off the inside of the second cylinder.

The system may include a laser light source that is optically coupled to the distal ends of both the first and second source light guides, and configured to generate a source beam of laser light, wherein the source beam is divided into the first and second beams of laser light. The system may include a first photodiode configured to receive and electrically respond to light from the first beam of laser light that is reflected off the inside of the first cylinder from the first reflected light guide. The system may also include a laser light source driver circuit coupled to the laser light source and configured to energize the laser light source upon receipt of a trigger pulse, and a timing circuit coupled to the laser light source driver configured to generate the trigger pulse and apply the trigger pulse to the laser light source driver circuit. The laser light source may be a laser diode. The system may include first and second photodiode amplifiers that are coupled to the first and second photodiodes, respectively.

Each of the first and second photodiode amplifiers may be configured to generate an output signal.

The system may also include a pulse expansion circuit, to which the first and second photodiode output signals are coupled.

The second ends of the plurality of second light guides may be optically coupled to a single light detector. The light detector may have an electrical output that is produced by light carried by at least two of the plurality of second light guides.

In accordance with a second embodiment of the invention, a method for determining the time-of-flight of laser light pulses in a plurality of hydraulic or pneumatic cylinders is provided, including the steps of generating a timing pulse in a timing circuit, conducting the timing pulse to a laser light source and responsively generating laser light pulse from the source, conducting a first portion of the pulse through a first optical fiber to a first cylinder, conducting the first portion into the first cylinder, reflecting the first portion off a first reflective surface coupled to a first piston in the first cylinder, receiving the first portion at a first photo diode and responsively generating a first electrical signal, conducting a second portion of the pulse through a second optical fiber to a second cylinder, conducting the second portion into the second cylinder, reflecting a second portion off a second reflective surface coupled to a second piston in the second cylinder, receiving the second portion at a second photo diode and suppressing the generation of the second electrical signal, providing the first electrical signal and the timing pulse to a comparator circuit and responsibly generating a first output signal indicative of a first time difference between the arrival of the timing pulse and the arrival of the first electrical signal at the comparator circuit.

The method may also include the steps of generating a second timing pulse in the timing circuit, conducting the second pulse to the laser light source and responsibly generating a second laser light pulse from the source, conducting a first portion of the second laser light pulse through the first optical fiber to the first cylinder, conducting the first portion of the second laser light pulse into the first cylinder, reflecting the first portion of the second

laser light pulse off the first reflective surface, receiving the first portion of the second laser light pulse at the first photo diode and suppressing the generation of a third electrical signal indicative of the time of arrival of the first portion of the second laser light pulse at the first photo diode, conducting a second portion of the second laser light pulse through the second optical fiber to the second cylinder, conducting the second portion of the second laser light pulse into the second cylinder, reflecting the second portion of the second laser light pulse off the second reflective surface, receiving the second portion of the second laser light pulse at a second photo diode and responsibly generating a fourth electrical signal indicative of the time of arrival of the second portion of the second laser light pulse at the second photo diode, providing the fourth electrical signal in the second timing pulse to the comparator circuit and responsibly generating a second output signal indicative of a second time difference between the arrival of the timing pulse and the second electrical signal at the comparator circuit.

The step of conducting the first timing pulse to the laser light source and responsively generating a second laser light pulse from the source may include the steps of optically coupling the laser light source to distal ends of the first and second optical fibers, and dividing the first laser light pulse into the first and second portions. The method may also include the steps of providing a laser light source driver circuit, coupling the laser light source to the driver circuit, applying the first and second timing pulses to the laser light source driver circuit, and energizing the laser light source responsive to the application of the first and second timing pulses to the driver circuit. The method may include the steps of providing a first photo diode amplifier and coupling the first photo diode amplifier to the first photo diode, providing a second photo diode amplifier and coupling the second photo diode amplifier to the second photo diode, generating a first gate signal in the timing circuit, applying the first gate signal to the first photo diode amplifier to permit the transmission of first electrical signal, generating a second gate signal in the timing circuit, and applying the second gate signal to the second photo diode amplifier to suppress the transmission of the second electrical signal. The method may include the step of configuring the first and second photo diode amplifiers to generate first and second amplifier output signals, respectively. The method may include the step of coupling the first and second photo diode amplifier

output signals and transmitting the coupled output signals to a pulse expansion circuit. The method may include the step of transmitting the first and second output signals to a pulse expansion circuit. The method may include the steps of generating an expanded pulse output signal in the pulse expansion circuit, and outputting the expanded pulse output signal from the pulse expansion circuit. The method may include the steps of providing a pulse comparator circuit, and inputting the expanded pulse output signal and the timing pulse into the pulse comparator circuit, and generating a time delay output signal in the pulse comparator circuit indicative of a time delay between the timing pulse and the expanded pulse output signal.

In accordance with a third embodiment of the invention, a method of determining the time-of-flight of laser light in a plurality of hydraulic or pneumatic cylinders includes the steps of transmitting a laser light pulse from a laser diode, dividing the laser light pulse into at least first and second sub-pulses, injecting the first and second sub-pulses into first and second cylinders, respectively, reflecting the first and second sub-pulses off first and second pistons in the first and second cylinders, respectively, transmitting the first and second reflected sub-pulses at two first and second photo diodes, respectively, generating first and second electrical signals in the first and second photo diodes that are indicative of the first and second times of arrival of the first and second sub-pulses at the first and second photo diodes, respectively, selectively coupling the first and second electrical signals in a first mode of operation to a pulse expansion circuit and a phase comparator circuit to generate a first time-of-flight signal on an output line of the phase comparator circuit that is indicative of the time-of-flight of the first sub-pulse and not of the second sub-pulse, repeating the foregoing steps with a second pulse of laser light, but in a second mode of operation wherein the phase comparator circuit generates a second time-of-flight signal on the output line that is indicative of the time-of-flight of the second sub-pulse and not of the first sub-pulse of the second pulse of laser light.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the following detailed description, taken in conjunction with the accompanying drawings, wherein like reference numerals refer to like parts, in which:

FIGURE 1 is a partial cross-sectional view of a hydraulic actuator having the laser-based reflective beam sensor and a control unit for generating the laser beam and calculating the position of the actuator wherein the laser light sources are located remotely from the actuator and cables including three fiber optic light guides couple the control unit to the actuator;

FIGURE 2 is a partial cross-sectional view of the embodiment of FIGURE 1 showing how the light guides are coupled to the cylinder;

FIGURE 3 is graph of laser light transmissivities through several different hydraulic fluids of various ages and types; and

FIGURE 4 illustrates an arrangement that includes several cylinders that are multiplexed together sharing common circuitry in accordance with the present invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIGURE 1 is a schematic view of a linear cylindrical actuator 10 in accordance with the present invention. Actuator 10 includes a cylinder 12 having an inner diameter 14 and two end caps 16, 18. Rod end cap 16 encloses one longitudinal end of the cylinder and has an opening 17 through which rod 24 passes. Opening 17 seals against the surface of the rod and prevents actuating fluid from leaking out. End cap 18 encloses the opposing end of the cylindrical potion of the cylinder and prevents actuating fluid from leaking out.

Actuator 10 also includes a piston assembly 20 which includes a piston 22 having an outside diameter 23 configured to seal against the inner diameter 14 of the cylinder and to slide longitudinally, back and forth, with respect to cylinder 12. Piston 22 is coupled to rod 24, which extends from the inside of the cylinder to the outside of the cylinder through

opening 17 and is fixed to piston 22 to move simultaneously with the piston. Surface 26 is a reflective surface fixed to move with piston 22 and is configured to reflect laser light that is introduced into the cylinder. Two ports 28, 30 are provided in the cylinder to introduce an operating fluid into the cylinder or remove the operating fluid from the cylinder. Extension cylinder port 28 is disposed in the cylinder such that fluid introduced into the port will cause the piston and piston rod to move in a direction that increases the overall length of the actuator 10. Retraction cylinder port 30 is disposed in the cylinder such that when a working fluid is introduced into the actuator through this port, it causes the piston assembly to move into the cylinder, or retract, thereby reducing the overall length of actuator 10. When the working fluid is removed from retraction cylinder port 30, rod 24 extends farther outside the cylinder, increasing the overall length of actuator 10.

The cylinder and piston assembly collectively define two internal cavities separated by the piston into which fluid may be introduced or removed. Extension cavity 32, when filled (through port 28) causes the piston assembly to extend, increasing the overall length of the actuator. At the same time, retraction cavity 34 is emptied. Similarly, when retraction cavity 34 is filled, through retraction cylinder port 30, retraction cavity 34 fills with fluid, extension cavity 32 empties fluid through extension cylinder port 28.

Excluding the effects due to the size of piston rod 24, actuator 10 has a predetermined internal fluid volume that does not change based upon the position of the piston. This volume (again, discarding the effects due to the size of piston rod 24) is equal to the sum of the volumes of extension cavity 32 and retraction cavity 34.

An optical coupler 34 is fixed in end cap 18 to communicate laser light into chamber 32 and to communicate laser light from chamber 32 outside the cylinder. The cap itself has a threaded external surface that engages mating threads in end cap 18. These threads serve to secure the coupler to the end cap and to prevent leakage of hydraulic fluid or air out of the cylinder. The coupler also serves to hold several optical fibers 36, 38 in a fixed relationship with respect to cylinder 12. Coupler 34 is preferably disposed along the centerline of cylinder 12 such that the cylinder and the coupler share a common cylindrical axis 40.

Referring now to FIGURE 2, coupler 34 supports eight optical fibers ranged in arcuate, preferably circular, pattern equidistantly spaced from the longitudinal cylindrical axis of the coupler. These fibers gather light that is reflected off surface 26 and conduct it out of the cylinder. Fiber 36 is disposed along axis 40 and conducts light from outside the cylinder into the cylinder. Light that is conducted into the cylinder through fiber 36 is directed towards reflective surface 26 on piston 22. It reflects off piston 22 and returns in a plurality of paths to each of optical fibers 28. These fibers receive the light at substantially the same time and conduct the light out of the cylinder. An optical multiplexer 42 is optically coupled to fibers 38 and joins their/there individual light beams into a single beam that exits multiplexer 42 in optical fiber 44. Thus, the light carried by optical coupler 44 is the combination of all the individual beams of light carried by optical fibers 38.

Referring now to FIGURE 1, optical fiber 44 is at its other end connected to optical coupler 46, which directs and focuses the light beam of fiber 44 to photodiode 48. When the light passes through coupler 46 and falls upon photodiode 48, it changes the conductivity of the photodiode causing a change in the current flowing through circuit 50. This change in current, or photodiode signal, is amplified by photodiode amplifier 52. The output of photodiode amplifier 52 is fed to pulse expansion circuit 54 which increases the width of the photodiode signal. Phase comparison circuit 56 receives two impulses: the expanded pulse from pulse expansion circuit 54 and a trigger pulse from timing circuit 58. By determining the time difference between the pulse of timing circuit 58 and the expanded pulse from circuit 54, phase comparison circuit 56 generates a signal indicative of the time delay between these two pulses. This time delay signal is output signal 60.

Timing circuit 58 generates periodic pulses on the order of once every tenth of a second. These two pulses are provided on two signal lines. Signal line 62, which goes to phase comparison circuit 56 and signal line 64, which goes to laser driver circuit 66. Laser driver circuit 66, when it receives this timing signal, generates a pulse that is applied to laser diode 68. Laser diode 68 turns the signal into a laser light pulse, which is transmitted through optical fiber 36 and coupler 34 into cylinder 12. The laser light pulse traverses

cavity 32, reflects off surface 26 and returns to optical fibers 38, which are held in coupler 34.

Referring back to phase comparison circuit 56, circuit 56 receives a pulse on line 62 generated by timing circuit 58. It also receives an expanded pulse from pulse expansion circuit 54. The difference in time of arrival of these two pulses is substantially equal to the amount of time it takes for the laser light pulse to travel from laser diode 68 to photodiode 48. Whenever piston 20 moves, both the path from laser diode 68 to the piston increases and the path from the piston to photodiode 48 increases. Since this is a linear device, for every inch of movement of piston 20 the path length changes by two inches.

Pulse expansion circuit 54 is disclosed in more detail in U.S. Patent No. 6,005,395 as the directional sampler 74. The output of pulse expansion circuit 54 is an equivalent-time replica of the reflected pulses received by photodiode 48.

Phase comparison circuit 56 is described in U.S. Patent No. 6,005,395 as directional set/reset circuit 100.

The output signal 60 is preferably in the form of a square wave having a pulse width indicative of the time required for the light emitted from laser diode 68 to travel through the system. Changes in the pulse width are preferably proportional to the distance the piston has traveled.

Referring now to FIGURE 2, we see a cross-section of the end of actuator 10 taken at Section 2-2 in FIGURE 1. The coupler 34 is fixed to optical fibers 38 that transmit the reflected light beam out of the cylinder. In the embodiment shown, there are eight optical fibers arranged in a circular pattern about optical fiber 36, which is also supported in coupler 34. Coupler 34 is preferably disposed within the cylinder, as shown in FIGURE 2, such that fiber 38 enters the cylinder substantially coaxial with longitudinal axis 40 of the cylinder. Each of the eight fibers 38 is preferably disposed equidistantly with respect to fiber 38 and is preferably spaced equidistantly apart from the others of fibers 38. In this manner, each fiber

has a corresponding fiber disposed on the opposing side of optical fiber 38 from which they are both equally spaced.

In addition, the longitudinal axis of each of the optical fibers 38 and optical fiber 36 are preferably parallel such that light transmitted into the cylinder through optical fiber 38 will reflect off surface 26 of piston 20 and return directly to coupler 34. If surface 26 is disposed in a substantially perpendicular orientation with respect to the longitudinal axes of fibers 38 and 36, substantially all the light that is emitted into cylinder 12 by optical fiber 38 will arrive back at coupler 34.

The benefit of having several optical fibers for receiving reflected light is two fold. First, a smaller diameter optical fiber can be spaced closer to fiber 36. This closer spacing means that it is in a better position to receive the reflected light that reflects off perpendicular reflective surface 26. Secondly, by providing several optical fibers, considerably more reflected light can be gathered and provided to photodiode 48. This provides a substantially larger pulse and reduces any the possibility that stray reflections will trigger photodiode 48.

To provide this additive effect, each of optical fibers 38 is preferably the same length. Thus, when reflected light is received substantially simultaneously at each of the end of optical fibers 38 in cylinder 12, these pulses will take substantially the same time to arrive at multiplexer 42. Since each of fibers 38 are multiplexed together, the light in each fiber 38 will be added and inserted into optical fiber 44. Thus, any reflected light falling simultaneously on the receiving ends of fibers 38 will be combined and arrive simultaneously at the photodiode.

The spacing between fiber 36 and each of fiber 38 is preferably small, on the order of one to two centimeters. More preferably it is between five and ten millimeters.

FIGURE 3 is a plot of transmissivity vs. wavelength. It measures the degree to which laser light is attenuated as it passes through hydraulic fluids of varying types. The types of hydraulic fluid tested include "J" type fluid with in-trained air, "J" type fluid, old "E" type fluid, old "F" type fluid, and old "G" type fluid as shown in the legend in FIGURE 3. These

types of hydraulic fluid are well known to engineers working with hydraulic fluids, and represent several of the most common fluids used in hydraulic systems today. The "E", "F" and "G" type fluids are "old" in that the fluids tested have been used in actual hydraulic equipment, and were not new. Three of the four hydraulic fluids that make up the J, E, F and G fluids are Case hydraulic fluids MS 1207 Hi Tran Plus, MS 1209 Hi Tran Ultra, and MS 1230. The reason these fluids were chosen was to see the degree to which aging and use of a hydraulic fluid would cause the optical characteristics of such fluid to degrade. The assumption is that degraded or "old" fluid by its accumulation of moisture, oxygen, and suspended particulates such as metal particles would not transmit laser light as readily as new hydraulic fluids. The chart in FIGURE 3 indicates the qualities of each of the aforementioned fluids. Note that the transmission of light is restricted almost entirely in the range of 500 – 1700 nanometers. Outside this range, there is virtually no transmission of light. Within this range, however, there are three separate sub-ranges in which a significant amount of light is transmitted. These ranges are 700-1150 nanometers, 1250-1400 nanometers, and 1450-1650 nanometers. The broadest of these three ranges is the band between 700 and 1150 nanometers. In this range, there are three significant sub-ranges in which transmissivity is substantial these include the sub-range of 700-900 nanometers, 950-1025 nanometers, and 1030-1150 nanometers. Each of these sub-bands has a local transmissivity maximum at 850, 970, and 1090 nanometers, respectively. The other two major bands have their respective maxima at 1315 nanometers and 1560 nanometers, respectively.

Note that, in comparing each of the hydraulic fluids, the peak transmissivities in each of the bands and sub-bands do not vary substantially from the peak transmissivities of the other peak transmissivities. Comparing the "G_old" to the "E_old" fluids, although the variations in transmissivity at each of their respective maxima varies from .1 (at 1090 nanometers) to .4 (at 850 nanometers), the wavelengths of these respective maxima are the same.

Based upon this empirical analysis, it is clear that as hydraulic fluid ages its transmissivity peaks do not shift. An appropriate high power laser diode for transmitting

light through the hydraulic fluid would therefore be preferably selected to have a wavelength at or near any of the local maxima shown in FIGURE 3. As that oil ages, and in the absence of any maxima wavelength shift, one would expect the transmissivity to drop, but not to shift radically based upon wavelength. For this reason, a laser diode having a frequency of 850, +80/-125 nanometers, 970+/-30 nanometers, or 1090+/-30 nanometers would be particularly preferred. While the other two major bands also exhibit strong transmissivity at their local maxima, due to the sudden and extreme drop-off on either side of the local maxima there less preferred. Nonetheless, even though they are less preferred, a laser diode having a wavelength of 1325, +/- 50 nanometers, or 1560 +/- 50 nanometers would also be acceptable.

FIGURE 4 illustrates an arrangement of multiple hydraulic cylinders with laser light sensors that are connected to a single laser diode. This arrangement permits a plurality of hydraulic or pneumatic cylinders to be monitored by a single pulse expansion circuit and phase comparator circuit. There are similarities between the circuit of FIGURE 1 as well as differences. First, we would like to discuss the similarities. The cylinders 10 are identical both in FIGURE 1 and FIGURE 4. The optical couplers 34 are also identical in both FIGURE 1 and FIGURE 4. The optical fibers and connectors extending from the cylinder to the photodiode amplifier are also identical in both figures. Furthermore, the laser driver 66 and laser diode 68 are also identical. Optical fiber 37' in FIGURE 4 differs from optical fiber 37 in FIGURE 1 in that it includes at least three separable sub-fibers that are joined together at a distal end located away from the three hydraulic cylinders and adjacent to the laser diode such that each of the three is positioned to gather a portion of the light generated by the laser diode. At the other end, each of the separable sub-fibers are separated and directed to each of three fiber optic connectors 39. The other end of these three optical fibers are held closely together and disposed in the optical path in front of laser diode 68. In this manner, laser light generated by laser diode 68 is transmitted into at least three fibers at once.

When laser diode 68 generates a pulse of light, that pulse is transmitted into each of the three optical fibers that are closely coupled to the laser diode. Since the three fibers are separated and connected to individual fiber optic connectors 39, the pulse of light travels down each of the three fibers through connectors 39, through each of three optical fibers 36

and into all three hydraulic actuators 10. The light pulses traverse cylinder 12, reflect off reflective surface 26 and return to optical couplers 34. Each of the individual fibers 38 for each of the couplers 34 receives a portion of the light, which is then merged at multiplexers 42. For each of the three cylinders, the reflected pulse of laser light then travels down optical fiber 44, through collimating lens assembly 46 and falls upon photodiode 48.

Thus, the light from laser diode 68 is received at three different photodiodes and three different photodiode amplifiers. Each pulse of light from laser diode 68 is therefore first divided into three separate optical fibers. The three pulses from these three fibers are reflected off a piston and the reflected pulses are then further sub-divided into two or more receiving optical fibers 38. For each actuator, the reflected optical pulses that are gathered by two or more individual fibers 38 are gathered together again and converted into a single optical pulse (with a greater amplitude than any of the three sub-divided pulses on fibers 38) and is applied to a corresponding photo diode amplifier 52' for that actuator.

The output of each photodiode amplifier 52' is joined to the other outputs, which are provided to pulse expansion circuit 54. The expanded pulse is then transmitted to phase comparator 56, which then provides the time-of-flight on line 60 for further processing.

In practical application, it is anticipated that each of the three actuators 10 will operate independently of the other. As a result, one piston may be very close to optical coupler 34 while another piston is far away. As time progresses, the two pistons may move towards one another, cross paths, and assume the opposite orientation, with the extended cylinder now retracted and the retracted cylinder now extended.

If pulse expansion circuit 54 simultaneously received signals from all three photodiode amplifiers whenever a pulse of light was generated by laser diode 68, it would become impossible for it to differentiate between the three cylinders. If the optical path lengths for the three cylinders were ever equal, due to movement of pistons 20, photodiode amplifiers 52 prime would transmit pulses at the same time. As the optical paths change

their relative lengths, it would become impossible to determine, as they separated, which pulse received by pulse expansion circuit 54 corresponded to which cylinder.

For this reason, timing circuit 58' is equipped to not only generate simultaneous pulses on line 62 and 64 (the lines coupled to phase comparator circuit 56 and laser driver 66) respectively, but also to selectively enable a single photodiode amplifier 52' and disable the other photo diode amplifiers 52' using one or more of gate signals: gate 1, gate 2, or gate 3.

In the preferred embodiment, each of photodiode amplifiers 52' will not transmit a pulse to pulse expansion circuit 54 unless they receive a corresponding gate signal on their corresponding gate signal line. When they do not transmit a pulse, they are "disabled", and vice-versa. Thus, timing circuit 58' generates a gate pulse on one of the gate signal lines at substantially the same time as it generates the timing pulse on line 62 and 64. If the gate signal is transmitted on gate signal line "gate 1" then only the pulse of light returning from the top most cylinder in FIGURE 4 will be transmitted by a photodiode amplifier to the pulse expansion circuit. The other two photodiode amplifiers 52', not receiving a gate signal, will not transmit a corresponding signal indicating that they received reflected light to pulse expansion circuit 54. In this manner, timing circuit 58' can selectively enable or disable a plurality of photodiode amplifiers, thereby preventing the transmission of one or more reflected light pulses in electrical form to pulse expansion circuit 54.

While the embodiments illustrated in the FIGURES and described above are presently preferred, it should be understood that these embodiments are offered by way of example only. The invention is not intended to be limited to any particular embodiment, but is intended to extend to various modifications that nevertheless fall within the scope of the appended claims.

**WHAT IS CLAIMED IS:**

1. A multiple cylinder position sensing system is provided comprising:

a first cylinder including:

a first source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a first beam of laser light at a first frequency from outside the cylinder to inside the cylinder; and

at least one first reflected light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the first beam of laser light that is reflected off the inside of the first cylinder;

a second cylinder including:

a second source light guide having a first end and a distal second end and extending from inside the cylinder to outside the cylinder and adapted to transmit at least a second beam of laser light at a first frequency from outside the cylinder to inside the cylinder; and

at least one second reflected light guide having a first end and a second end and extending from inside the cylinder to outside the cylinder and configured to receive light from the second beam of laser light that is reflected off the inside of the second cylinder.

2. The system of Claim 1, further comprising a laser light source that is optically coupled to the distal ends of both the first and second source light guides, and configured to generate a source beam of laser light, wherein the source beam is divided into the first and second beams of laser light.

3. The system of Claim 2, further comprising a first photodiode configured to receive and electrically respond to light from the first beam of laser light that is reflected off the inside of the first cylinder from the first reflected light guide.

4. The system of Claim 3, further comprising:

a laser light source driver circuit coupled to the laser light source and configured to energize the laser light source upon receipt of a trigger pulse; and

a timing circuit coupled to the laser light source driver configured to generate the trigger pulse and apply the trigger pulse to the laser light source driver circuit.

5. The system of Claim 4, wherein the laser light source is a laser diode.

6. The system of Claim 5, further comprising first and second photodiode amplifiers that are coupled to the first and second photodiodes, respectively.

7. The system of Claim 6, wherein each of the first and second photodiode amplifiers is configured to generate an output signal.

8. The system of Claim 7, further comprising a pulse expansion circuit, wherein the first and second photodiode output signals are coupled to the pulse expansion circuit.

9. A method for determining the time-of-flight of laser light pulses in a plurality of hydraulic or pneumatic cylinders, the method including the steps of:

generating a first timing pulse in a timing circuit;

conducting the first timing pulse to a laser light source and responsively generating a first laser light pulse from the source;

conducting a first portion of the first laser light pulse through a first optical fiber to a first cylinder;

conducting the first portion of the first laser light pulse into the first cylinder;

reflecting the first portion off a first reflective surface coupled to a first piston in the first cylinder;

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receiving the first portion of the first laser light pulse at a first photodiode and responsively generating a first electrical signal indicative of the time of arrival of the first portion of the first laser light pulse at the first photodiode;

conducting a second portion of the first laser light pulse through a second optical fiber to a second cylinder;

conducting the second portion of the first laser light pulse into the second cylinder;

reflecting the second portion of the first laser light pulse off a second reflective surface coupled to a second piston in the second cylinder;

receiving the second portion of the first laser light pulse at a second photodiode and suppressing the transmission of a second electrical signal indicative of the time of arrival of the second portion of the first laser light pulse at the second photodiode; and

providing the first electrical signal and the timing pulse to a comparator circuit and responsively generating a first output signal indicative of a first time difference between the arrival of the timing pulse and the arrival of the first electrical signal at the comparator circuit.

10. The method of Claim 9, further comprising the steps of:

generating a second timing pulse in the timing circuit;

conducting the second timing pulse to the laser light source and responsively generating a second laser light pulse from the source;

conducting a first portion of the second laser light pulse through the first optical fiber to the first cylinder;

conducting the first portion of the second laser light pulse into the first cylinder;

reflecting the first portion of the second laser light pulse off the first reflective surface;

receiving the first portion of the second laser light pulse at the first photodiode and suppressing the generation of a third electrical signal indicative of the time of arrival of the first portion of the second laser light pulse at the first photodiode;

conducting a second portion of the second laser light pulse through the second optical fiber to the second cylinder;

conducting the second portion of the second laser light pulse into the second cylinder;

reflecting the second portion of the second laser light pulse off the second reflective surface;

receiving the second portion of the second laser light pulse at a second photodiode and responsively generating a fourth electrical signal indicative of the time of arrival of the second portion of the second laser light pulse at the second photodiode; and

providing the fourth electrical signal and the second timing pulse to the comparator circuit and responsively generating a second output signal indicative of a second time difference between the arrival of the timing pulse and the second electrical signal at the comparator circuit.

11. The method of Claim 9, wherein the step of conducting the first timing pulse to the laser light source and responsively generating a second laser light pulse from the source includes the steps of:

optically coupling the laser light source to distal ends of the first and second optical fibers; and

dividing the first laser light pulse into the first and second portions.

12. The method of Claim 11, further comprising the steps of:

providing a laser light source driver circuit;

coupling the laser light source to the driver circuit;

applying the first and second timing pulses to the laser light source driver circuit; and

energizing the laser light source responsive to the application of the first and second timing pulses to the driver circuit.

13. The method of Claim 9, further comprising the steps of:

providing a first photodiode amplifier and coupling the first photodiode amplifier to the first photodiode;

providing a second photodiode amplifier and coupling the second photodiode amplifier to the second photodiode;

generating a first gate signal in the timing circuit;

applying the first gate signal to the first photodiode amplifier to permit the transmission of the first electrical signal;

generating a second gate signal in the timing circuit; and

applying the second gate signal to the second photodiode amplifier to suppress the transmission of the second electrical signal.

14. The method of Claim 13, further comprising the step of:

configuring the first and second photodiode amplifiers to generate first and second amplifier output signals, respectively.

15. The method of Claim 14, further comprising the step of:

coupling the first and second photodiode amplifier output signals; and

transmitting the coupled output signals to a pulse expansion circuit.

16. The method of Claim 14, further comprising the step of:

transmitting the first and second output signals to a pulse expansion circuit.

17. The method of Claim 16 further comprising the steps of:

generating an expanded pulse output signal in the pulse expansion circuit; and

outputting the expanded pulse output signal from the pulse expansion circuit.

18. The method of Claim 17, further comprising the steps of:

providing a pulse comparator circuit; and

inputting the expanded pulse output signal and the timing pulse into the pulse comparator circuit; and

generating a time delay output signal in the pulse comparator circuit indicative of a time delay between the timing pulse and the expanded pulse output signal.

19. A method of determining the time-of-flight of laser light in a plurality of hydraulic or pneumatic cylinders comprising the steps of:

transmitting a laser light pulse from a laser diode;

dividing the laser light pulse into at least first and second sub-pulses;

injecting the first and second sub-pulses into first and second cylinders, respectively;

reflecting the first and second sub-pulses off first and second pistons in the first and second cylinders, respectively;

receiving the first and second reflected sub-pulses to first and second photodiodes, respectively;

generating first and second electrical signals in the first and second photodiodes that are indicative of the first and second times of arrival of the first and second sub-pulses at the first and second photodiodes, respectively;

selectively coupling the first and second electrical signals in a first mode of operation to a pulse expansion circuit and a phase comparator circuit to generate a first time-of-flight signal on an output line of the phase comparator circuit that is indicative of the time-of-flight of the first sub-pulse and not of the second sub-pulse; and

repeating the foregoing steps with a second pulse of laser light but in a second mode of operation wherein the phase comparator circuit generates a second time-of-flight signal on the output line that is indicative of the time-of-flight of the second sub-pulse and not of the first sub-pulse of the second pulse of laser light.

## ABSTRACT OF THE DISCLOSURE

A hydraulic actuator is disclosed having a cylinder with a piston that is moved by hydraulic fluid. A laser diode emits a pulse or pulses of light that form laser light beam. These pulses are provided to two or more optical fibers that extend into two or more corresponding cylinders. For each of these cylinders, the optical fiber enters the cylinder at one end of the cylinder and directs a laser beam into the cylinder, and off the piston where the beam is reflected. The reflected beam then exits the cylinder through at least two corresponding optical fibers disposed on either side of the fiber that conducted the light into the cylinder. Each of the optical fibers that receives reflected light is joined together with the others of the optical fibers into one fiber that carries the reflected beam of light to a photo-diode located remote from the cylinder. Each of the photo diodes for each of the two or more cylinders has a corresponding photo diode amplifier. The output of these amplifiers are coupled together and provided to a pulse expansion circuit. The timing circuit that generates the pulse that triggers the laser diode also generates gate pulses for each of the photo diode amplifiers. These gate signals suppress the output of all but one of the photo diode amplifiers. In this manner, the pulse expansion circuit and phase comparator circuits that receive the photo diode amplifier signals will generate an output signal indicative of the time-of-flight of the laser light pulse in only one cylinder at a time. This permits the system to select a specific cylinder and generate a signal indicative of the position of the piston within the cylinder: the time-of-flight of the laser light pulse.

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|---|---|---|---|
| **To:** | Kevin Pyo | **Fax:** | 703-746-4818 |
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Docket: 13937
S/N 09/872,895
Multi-Fiber Multi-Cylinder Position Method And Apparatus Using Time Of Flight Technique

Attached are the copies of the reference requested for the above-identified docket.